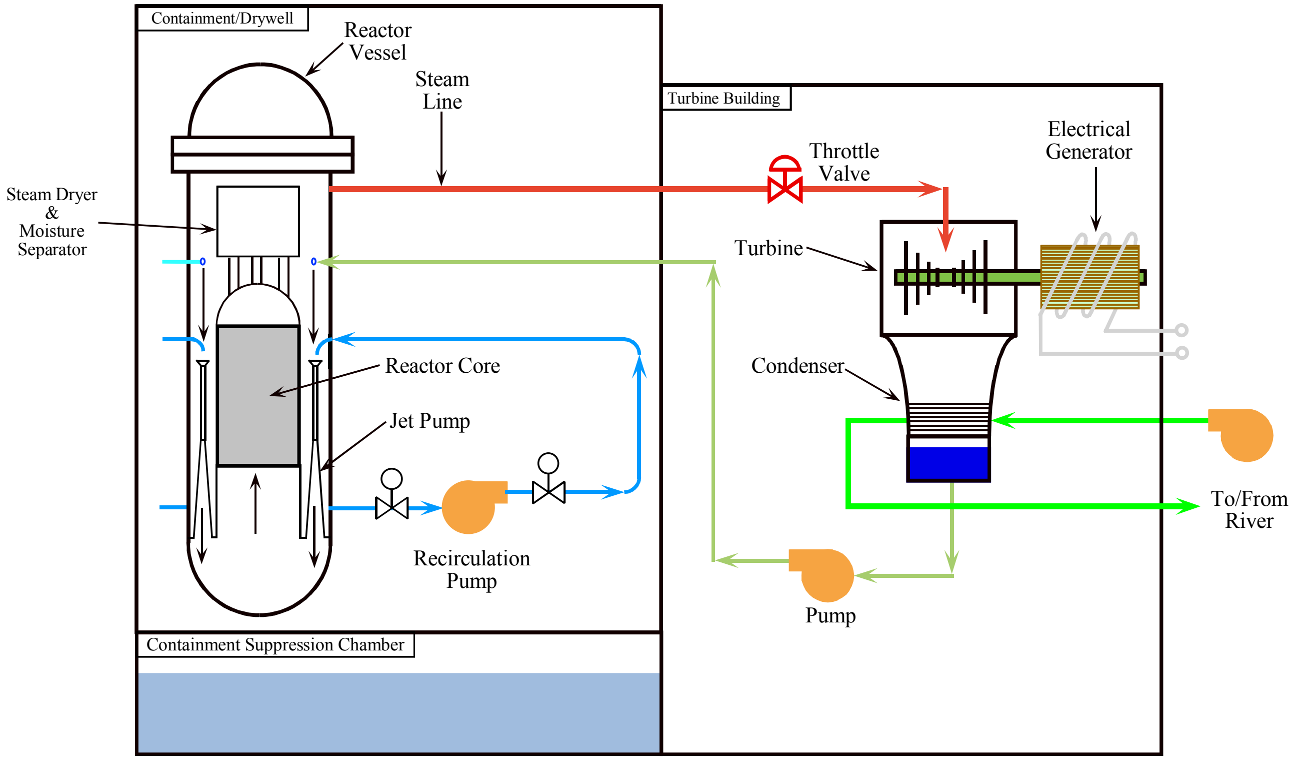
Boiling Water Reactor (BWR) Systems

This chapter will discuss the purposes of some of the major systems and components associated with a boiling water reactor (BWR) in the generation of electrical power.



Boiling Water Reactor Plant

Inside the boiling water reactor (BWR) vessel, a steam water mixture is produced when very pure water (reactor coolant) moves upward through the core absorbing heat. The major difference in the operation of a BWR from other nuclear systems is the steam void formation in the core. The steam-water mixture leaves the top of the core and enters the two stages of moisture separation, where water droplets are removed before the steam is allowed to enter the steam line. The steam line, in turn, directs the steam to the main turbine causing it to turn the turbine and the attached electrical generator. The unused steam is exhausted to the condenser where it is condensed into water. The resulting water is pumped out of the condenser with a series of pumps and back to the reactor vessel. The recirculation pumps and jet pumps allow the operator to vary coolant flow through the core and change reactor power.

BWR Reactor Vessel Assembly

The reactor vessel assembly, shown on page 3-4, consists of the reactor vessel and its internal components, including the core support structures, core shroud, moisture removal equipment, and jet pump assemblies. The purposes of the reactor vessel assembly are to:

- House the reactor core,
- Serve as part of the reactor coolant pressure boundary,
- Support and align the fuel and control rods,
- Provide a flow path for circulation of coolant past the fuel,
- Remove moisture from the steam exiting the core, and
- Provide a refloodable volume for a loss of coolant accident.

The reactor vessel is vertically mounted within the drywell and consists of a cylindrical shell with an integral rounded bottom head. The top head is also rounded in shape but is removable via the stud and nut arrangement to facilitate refueling operations. The vessel assembly is supported by the vessel support skirt (20) which is mounted to the reactor vessel support pedestal.

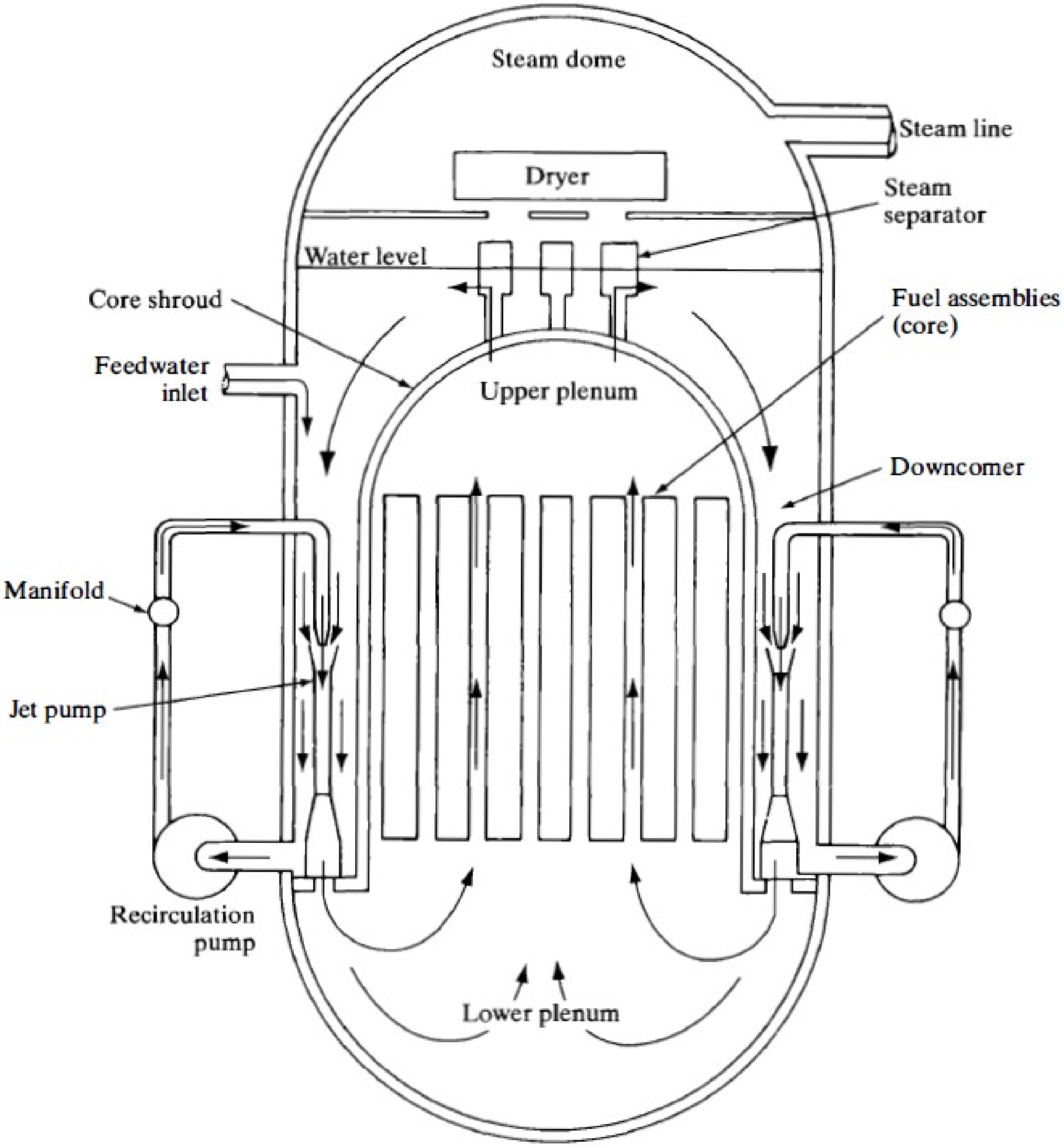
The internal components of the reactor vessel are supported from the bottom head and/or vessel wall. The reactor core is made up of fuel assemblies (15), control rods (16), and neutron monitoring instruments (24). The structure surrounding the active core consists of a core shroud (14), core plate (17), and top guide (12). The components making up the remainder of the reactor vessel internals are the jet pump assemblies (13), steam separators (6), steam dryers (3), feedwater spargers (8), and core spray spargers (11). The jet pump assemblies are located in the region between the core shroud and the vessel wall, submerged in water. The jet pump assemblies are arranged in two semicircular groups of ten, with each group being supplied by a separate recirculation pump.

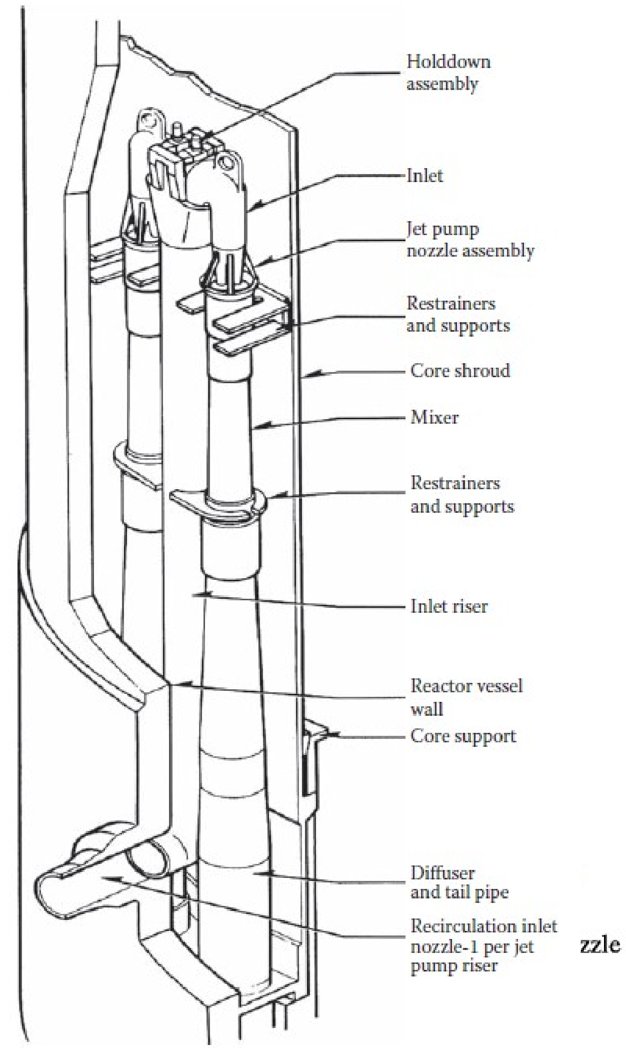
The emergency core cooling systems, penetrations number 5 and 9, and the reactor vessel designs are compatible to ensure that the core can be adequately cooled following a loss of reactor coolant. The worst case loss of coolant accident, with respect to core cooling, is a recirculation line break (penetrations number 18 and 19). In this event, reactor water level decreases rapidly, uncovering the core. However, several emergency core cooling systems automatically provide makeup water to the nuclear core within the shroud, providing core cooling.

The control cell assembly (page 3-5) is representative for boiling water reactor 1 through 6. Each control cell consists of a control rod (7) and four fuel assemblies that surround it. Unlike the pressurized water reactor fuel assemblies, the boiling water reactor fuel bundle is enclosed in a fuel channel (6) to direct coolant up through the fuel assembly and act as a bearing surface for the control rod. In addition, the fuel channel protects the fuel during refueling operations. The power of the core is regulated by movement of bottom entry control rods.

Table 11.3. Parameters for a typical 1000 MW(e) BWR sold in the early 1970s.

POWER		**REACTOR PRESSURE VESSEL**	
thermal output	3830 MW	inside diameter	6.4 m
electrical output	1330 MW(e)	total height	22.1 m
efficiency	0.34	wall thickness	15 cm
CORE		**FUEL**	
length	3.76 m	cylindrical fuel pellets	UO_2
diameter	4.8 m	pellet diameter	10.57 mm
specific power	25.9 kW/kg(U)	rod outer diameter	12.52 mm
power density	56 kW/L	zircaloy clad thickness	0.864 mm
av. linear heat rate	20.7 kW/m	rod lattice pitch	16.3 mm
rod surface heat flux		rods/assembly (8×8)	62
average	0.51 MW/m^2	assembly width	13.4 cm
maximum	1.12 MW/m^2	assembly height	4.48 m
		fuel assemblies in core	760
REACTOR COOLANT SYSTEM		fuel loading	168×10^3 kg
operating pressure	7.17 MPa	av. initial enrichment $\%^{235}U$	2.6%
	(1040 psia)	equil. enrichment % ^{235}U	1.9%
feedwater temperature	216 °C	discharge fuel burnup	27.5 GWd/tU
outlet steam temperature	290 °C		
outlet steam flow rate	7.5×10^6 kg/h	**REACTIVITY CONTROL**	
core flow rate	51×10^6 kg/h	no. control elements	193
core void fraction (av.)	0.37	shape	cruciform
core void fraction (max.)	0.75	overall length	4.42 m
no. in-core jet pumps	24	length of poison section	3.66 m
no. coolant pumps/loops	2	neutron absorber	boron carbide
		burnable poison in fuel	gadolinium





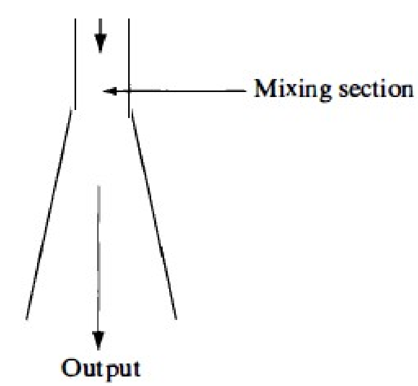
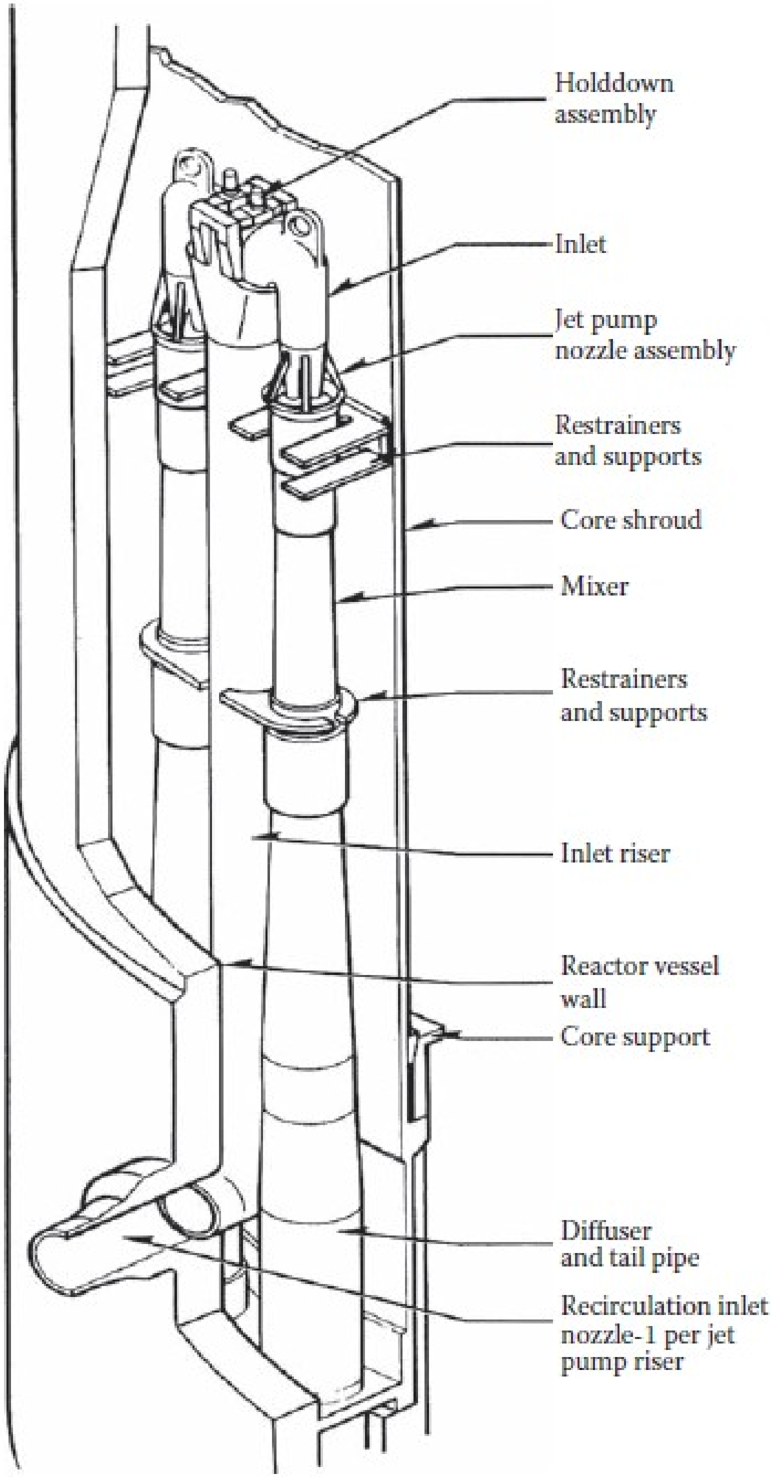
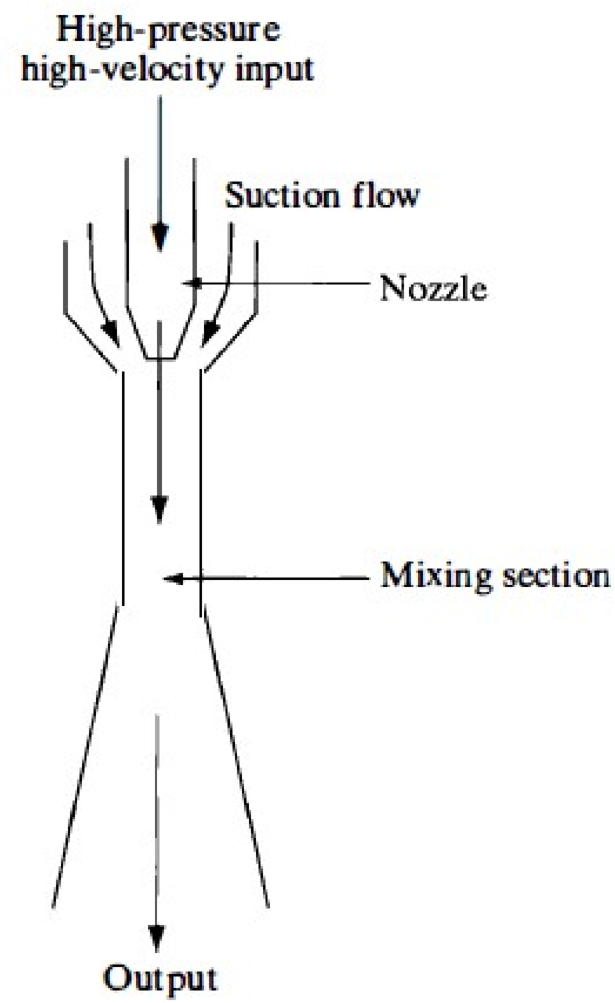
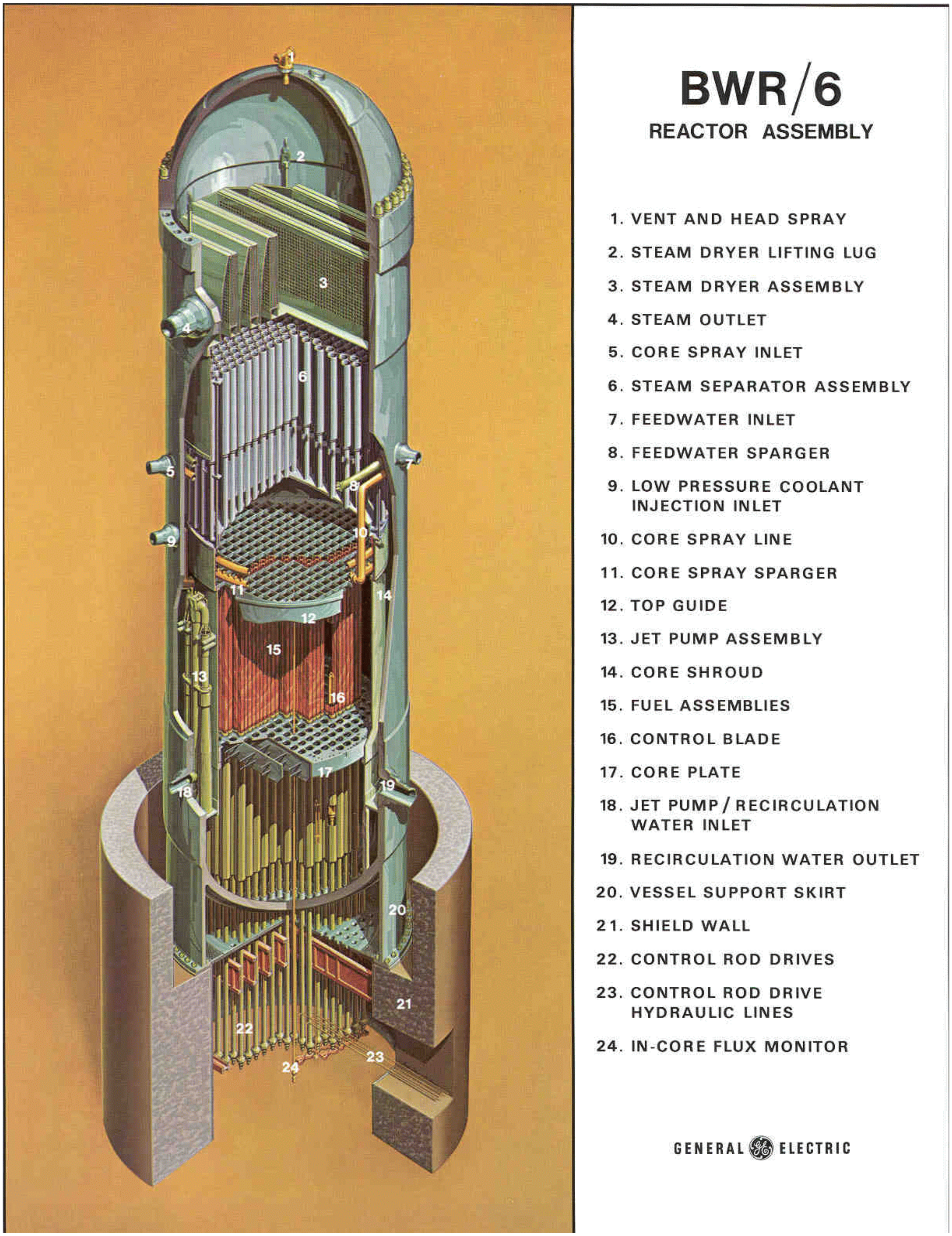


Figure 4.11 Cross-sectional view of a boiling-water reactor. The motion of the water is shown by arrows. (Courtesy of General Electric Company.)


Holddown
assembly
Inlet
Jet pump
nozzle assembly
Restrainers
and supports
Core shroud
Mixer
Restrainers
and supports
Inlet riser
Reactor vessel
wall
Core support
Diffuser
and tail pipe
Recirculation inlet
nozzle-1 per jet
pump riser


High-pressure
high-velocity input
Suction flow
Nozzle
Mixing section
Output



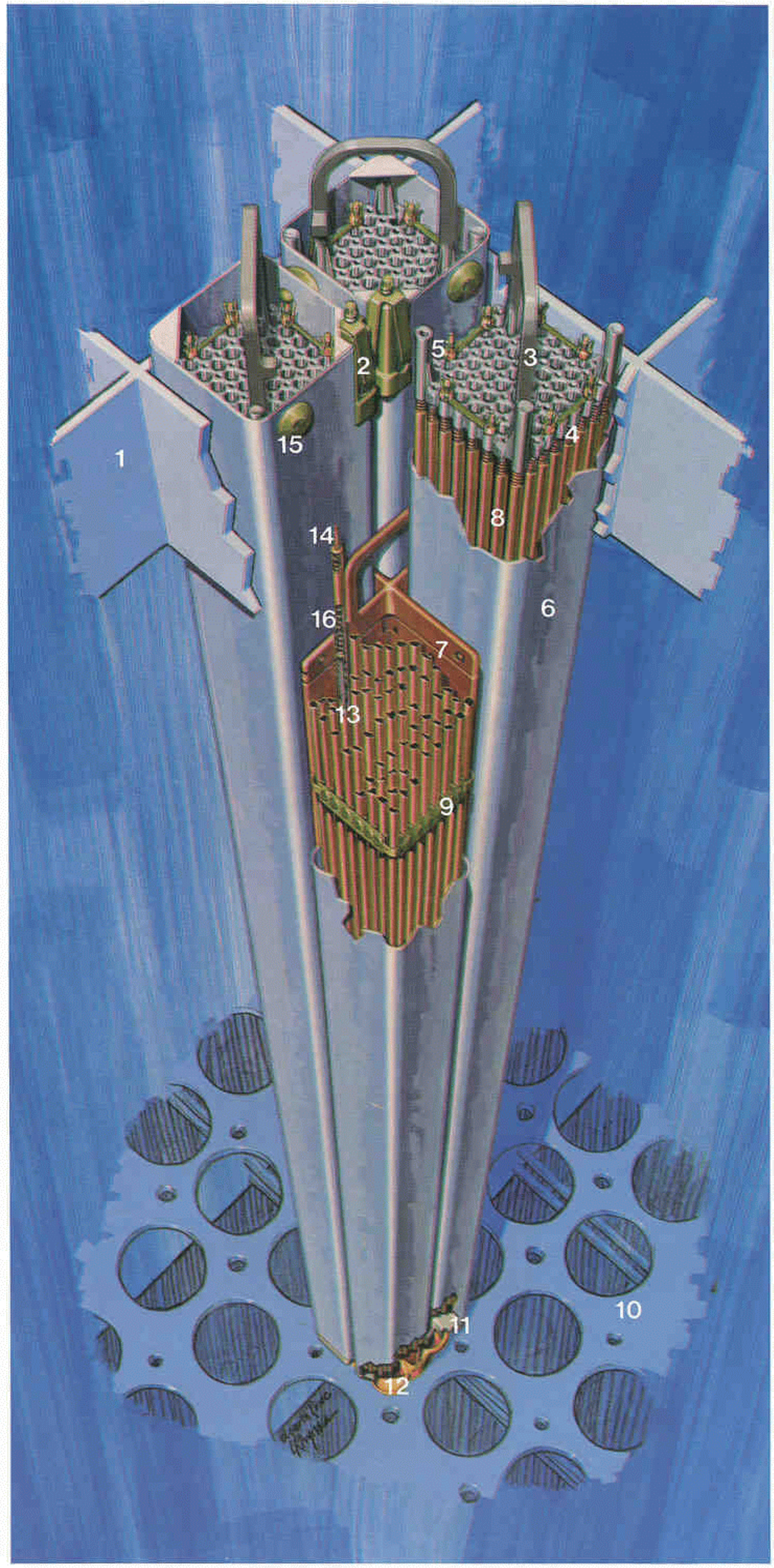
BWR 6 Reactor Vessel

BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

1. TOP FUEL GUIDE
2. CHANNEL FASTENER
3. UPPER TIE PLATE
4. EXPANSION SPRING
5. LOCKING TAB
6. CHANNEL
7. CONTROL ROD
8. FUEL ROD
9. SPACER
10. CORE PLATE ASSEMBLY
11. LOWER TIE PLATE
12. FUEL SUPPORT PIECE
13. FUEL PELLETS
14. END PLUG
15. CHANNEL SPACER
16. PLENUM SPRING

GENERAL ELECTRIC

GEZ-4383



BWR 6 Fuel Assembly

BWR/6 FUEL ASSEMBLIES & CONTROL ROD MODULE

1.TOP FUEL GUIDE
2.CHANNEL FASTENER
3.UPPER TIE PLATE
4.EXPANSION SPRING
5.LOCKING TAB
6.CHANNEL
7.CONTROL ROD
8.FUEL ROD
9.SPACER
10.CORE PLATE ASSEMBLY
11.LOWER TIE PLATE
12.FUEL SUPPORT PIECE
13.FUEL PELLETS
14.END PLUG
15.CHANNEL SPACER
16.PLENUM SPRING

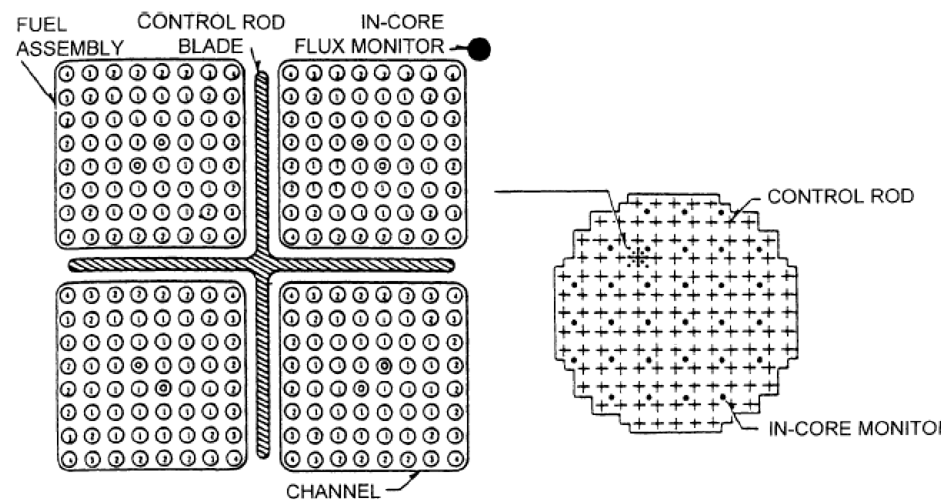
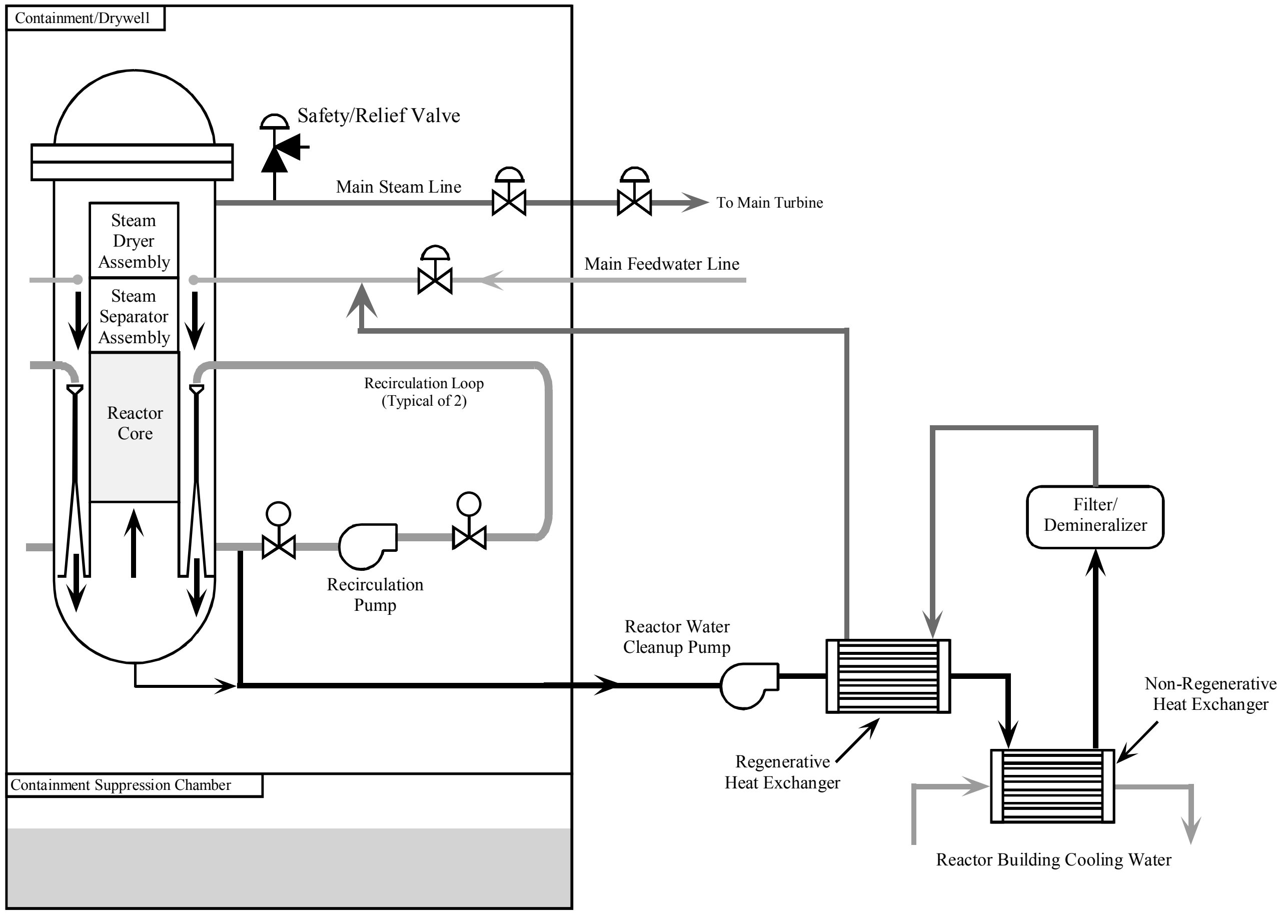
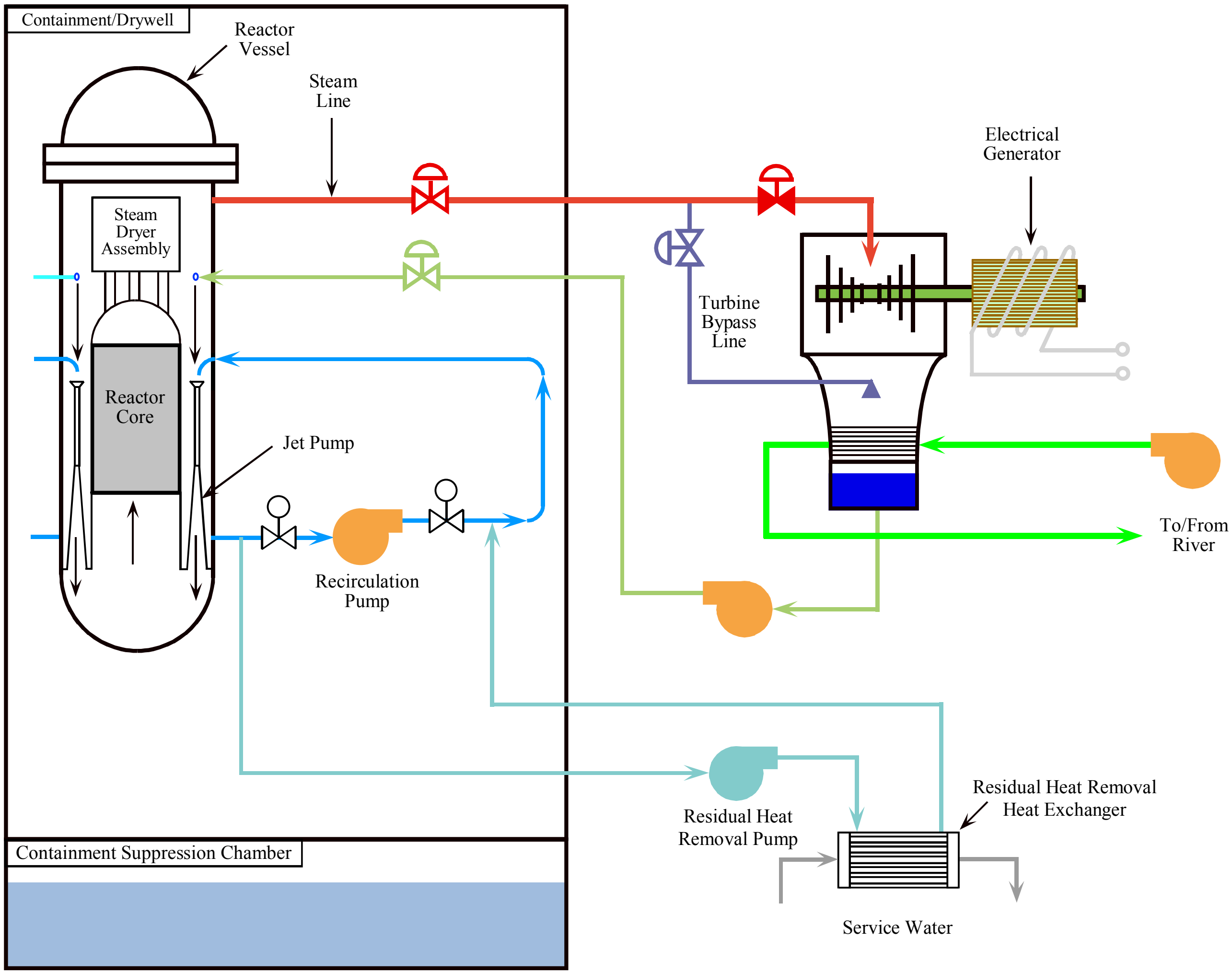


Fig. 7.5 Four-assembly fuel module for a boiling water reactor. (Courtesy of General Electric Company.)



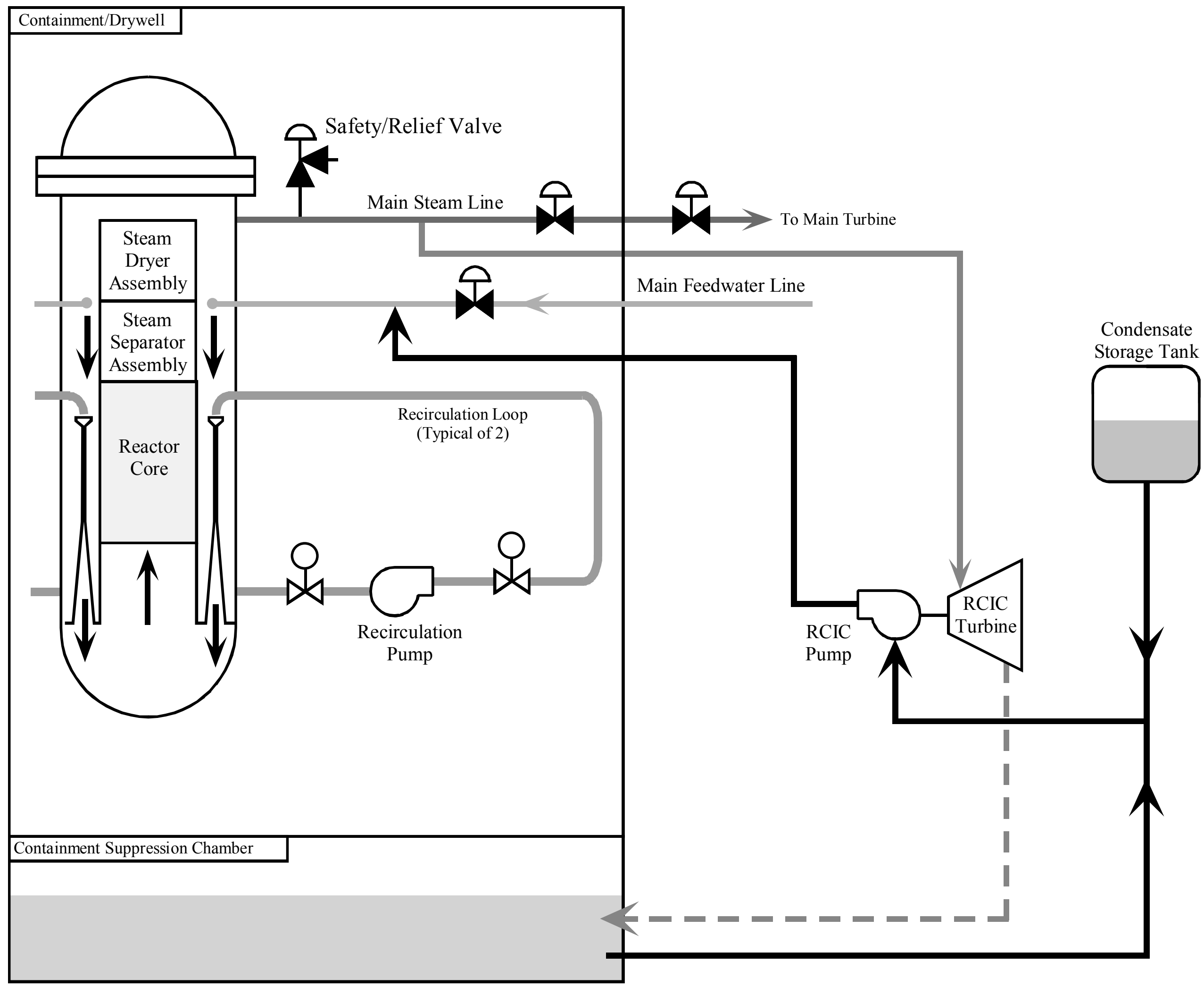
Reactor Water Cleanup System

The purpose of the reactor water cleanup system (RWCU) is to maintain a high reactor water quality by removing fission products, corrosion products, and other soluble and insoluble impurities. The reactor water cleanup pump takes water from the recirculation system and the vessel bottom head and pumps the water through heat exchangers to cool the flow. The water is then sent through filter/demineralizers for cleanup. After cleanup, the water is returned to the reactor vessel via the feedwater piping.



Decay Heat Removal

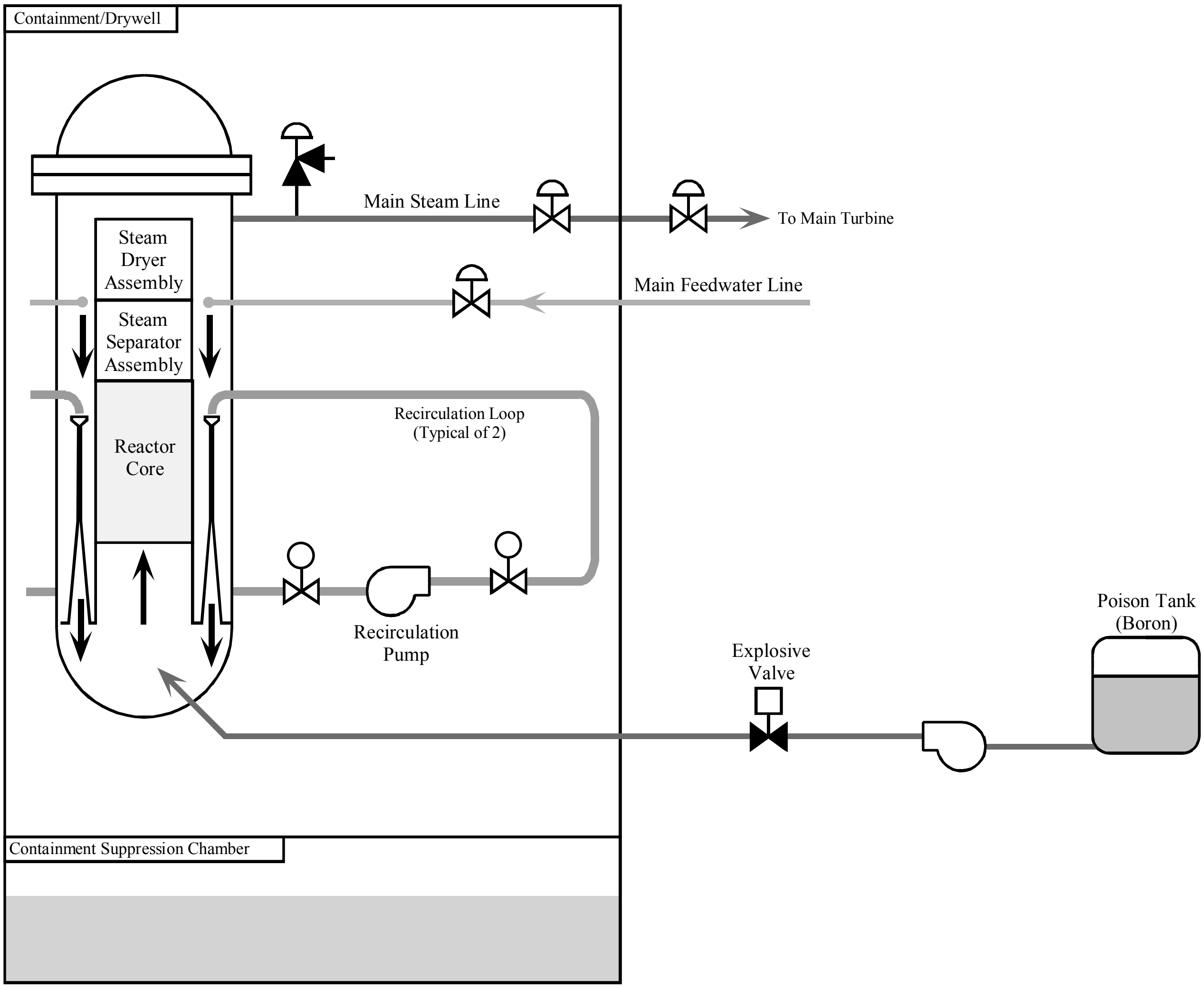
Heat is removed during normal power operation by generating steam in the reactor vessel and then using that steam to generate electrical energy. When the reactor is shutdown, the core will still continue to generate decay heat. The heat is removed by bypassing the turbine and dumping the steam directly to the condenser. The shutdown cooling mode of the residual heat removal (RHR) system is used to complete the cooldown process when pressure decreases to approximately 50 psig. Water is pumped from the reactor recirculation loop through a heat exchanger and back to the reactor via the recirculation loop. The recirculation loop is used to limit the number of penetrations into the reactor vessel.



Reactor Core Isolation Cooling

The reactor core isolation cooling (RCIC) system provides makeup water to the reactor vessel for core cooling when the main steam lines are isolated and the normal supply of water to the reactor vessel is lost. The RCIC system consists of a turbine-driven pump, piping, and valves necessary to deliver water to the reactor vessel at operating conditions.

The turbine is driven by steam supplied by the main steam lines. The turbine exhaust is routed to the suppression pool. The turbine-driven pump supplies makeup water from the condensate storage tank, with an alternate supply from the suppression pool, to the reactor vessel via the feedwater piping. The system flow rate is approximately equal to the steaming rate 15 minutes after shutdown with design maximum decay heat. Initiation of the system is accomplished automatically on low water level in the reactor vessel or manually by the operator.



Standby Liquid Control System

The standby liquid control system injects a neutron poison (boron) into the reactor vessel to shutdown the chain reaction, independent of the control rods, and maintains the reactor shutdown as the plant is cooled to maintenance temperatures.

The standby liquid control system consists of a heated storage tank, two positive displacement pumps, two explosive valves, and the piping necessary to inject the neutron absorbing solution into the reactor vessel. The standby liquid control system is manually initiated and provides the operator with a relatively slow method of achieving reactor shutdown conditions.

Emergency Core Cooling Systems

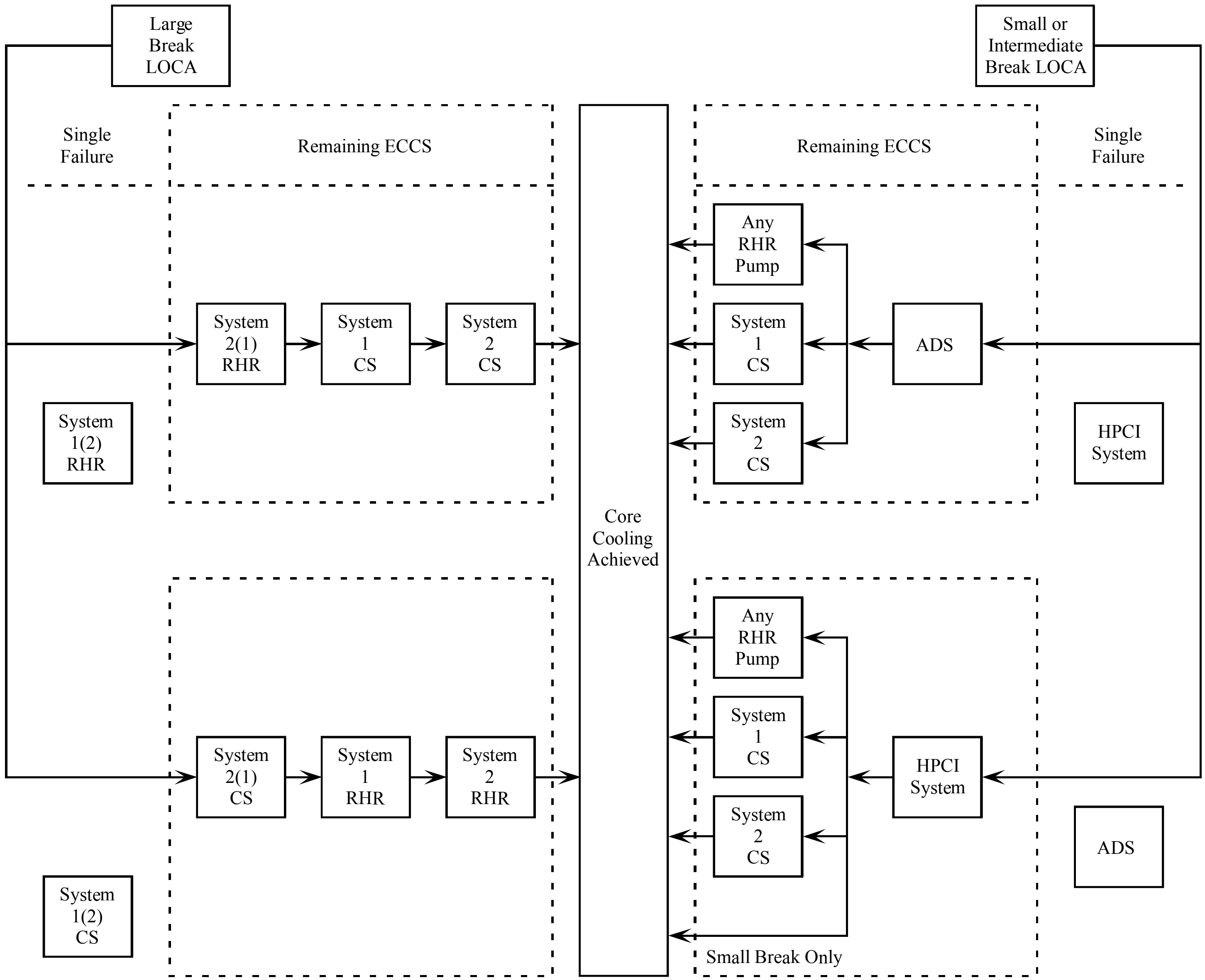
The emergency core cooling systems (ECCS) provide core cooling under loss of coolant accident conditions to limit fuel cladding damage. The emergency core cooling systems consist of two high pressure and two low pressure systems. The high pressure systems are the high pressure coolant injection (HPCI) system and the automatic depressurization system (ADS). The low pressure systems are the low pressure coolant injection (LPCI) mode of the residual heat removal system and the core spray (CS) system.

The manner in which the emergency core cooling systems operate to protect the core is a function of the rate at which reactor coolant inventory is lost from the break in the nuclear system process barrier. The high pressure coolant injection system is designed to operate while the nuclear system is at high pressure. The core spray system and low pressure coolant injection mode of the residual heat removal system are designed for operation at low pressures. If the break in the nuclear system process barrier is of such a size that the loss of coolant exceeds the capability of the high pressure coolant injection system, reactor pressure decreases at a rate fast enough for the low pressure emergency core cooling systems to commence coolant injection into the reactor vessel in time to cool the core.

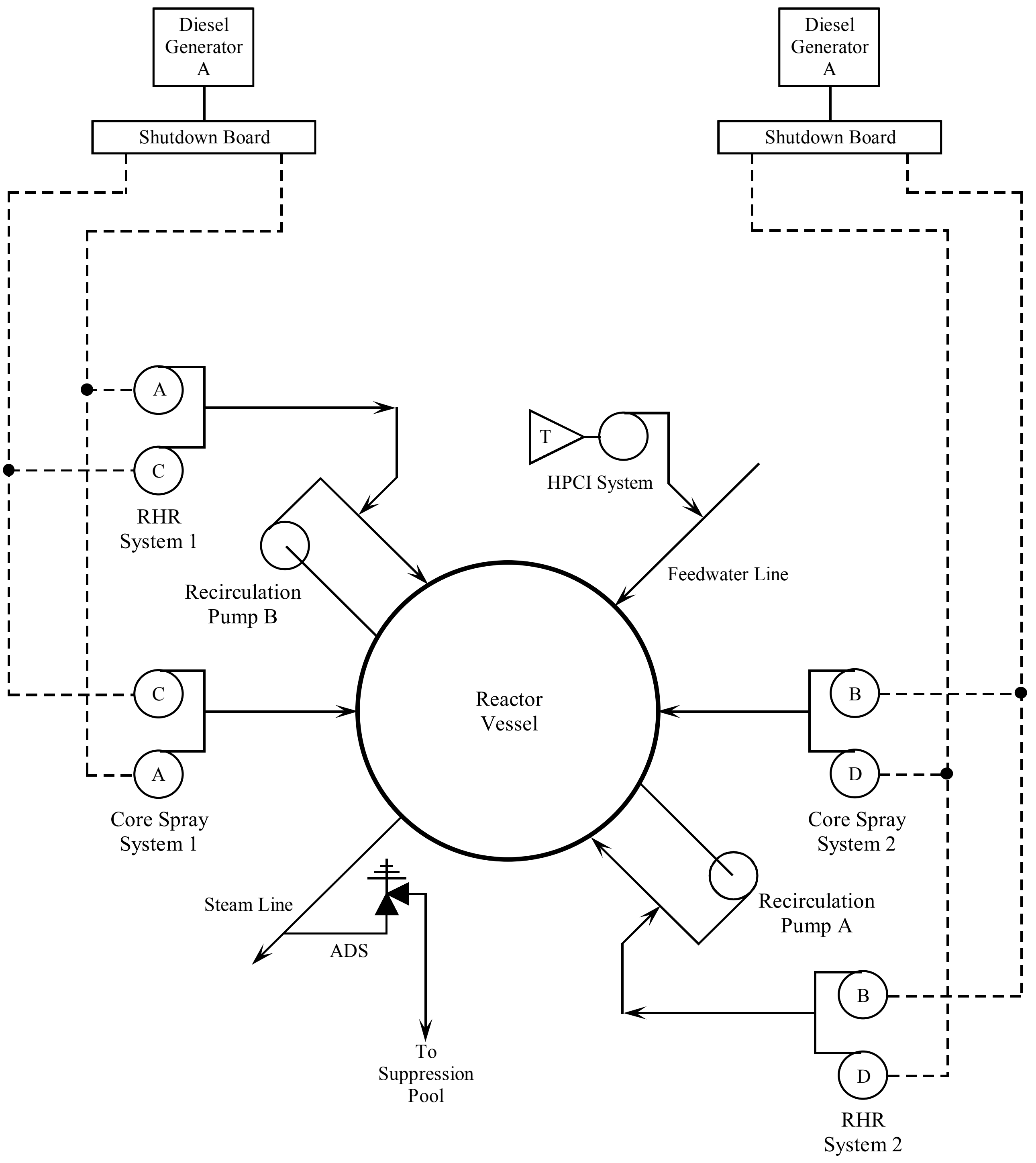
Automatic depressurization is provided to automatically reduce reactor pressure if a break has occurred and the high pressure coolant injection system is inoperable. Rapid depressurization of the reactor is desirable to permit flow from the low pressure emergency core cooling systems so that the temperature rise in the core is limited to less than regulatory requirements.

If, for a given break size, the high pressure coolant injection system has the capacity to make up for all of the coolant loss, flow from the low pressure emergency core cooling systems is not required for core cooling protection until reactor pressure has decreased below approximately 100 psig.

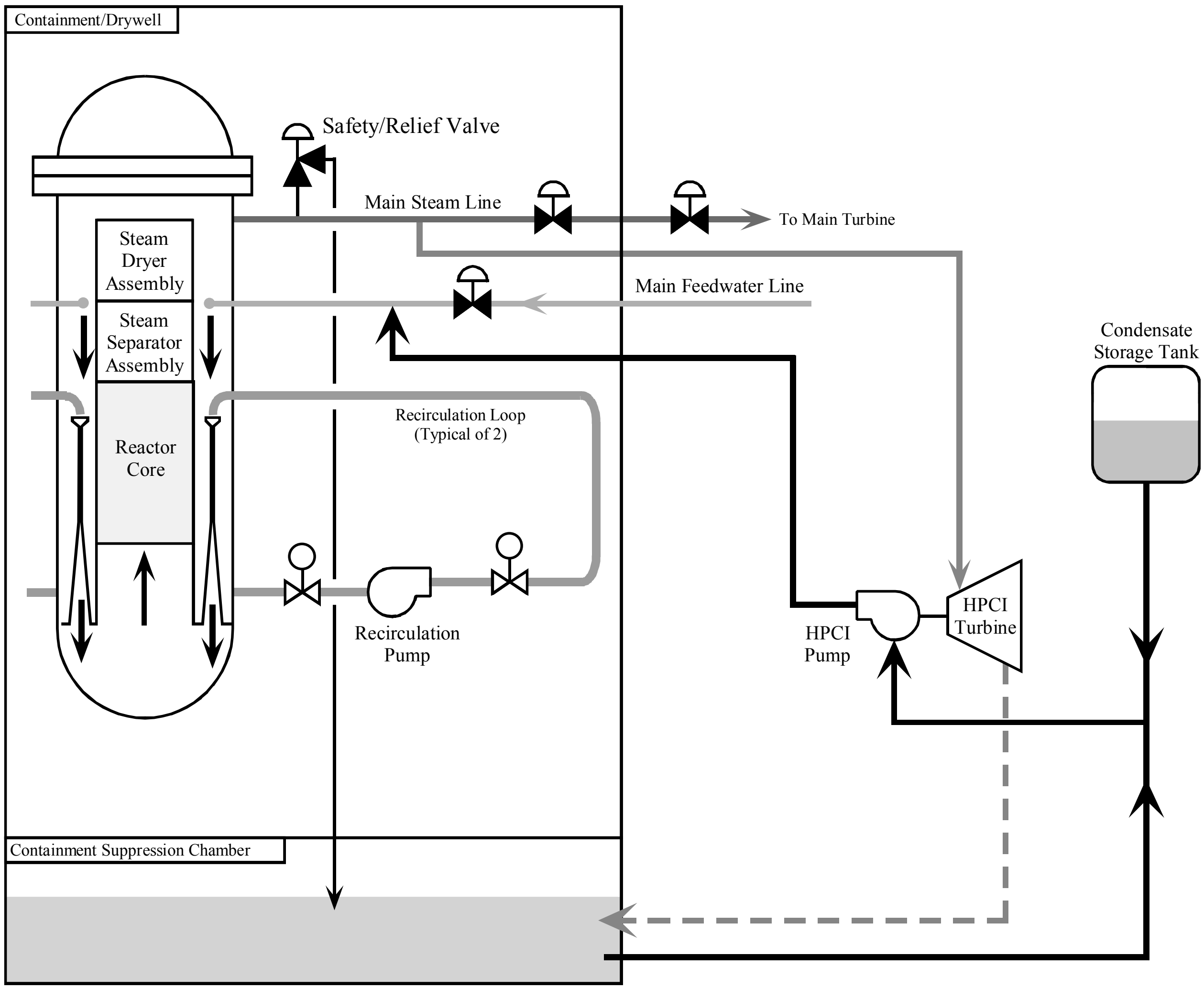
The performance of the emergency core cooling systems as an integrated package can be evaluated by determining what is left after the postulated break and a single failure of one of the emergency core cooing systems. The remaining emergency core cooling systems and components must meet the 10 CFR requirements over the entire spectrum of break locations and sizes. The integrated performance for small, intermediate, and large sized breaks is shown on pages 3-11 and 3-12.



ECCS Integrated Performance



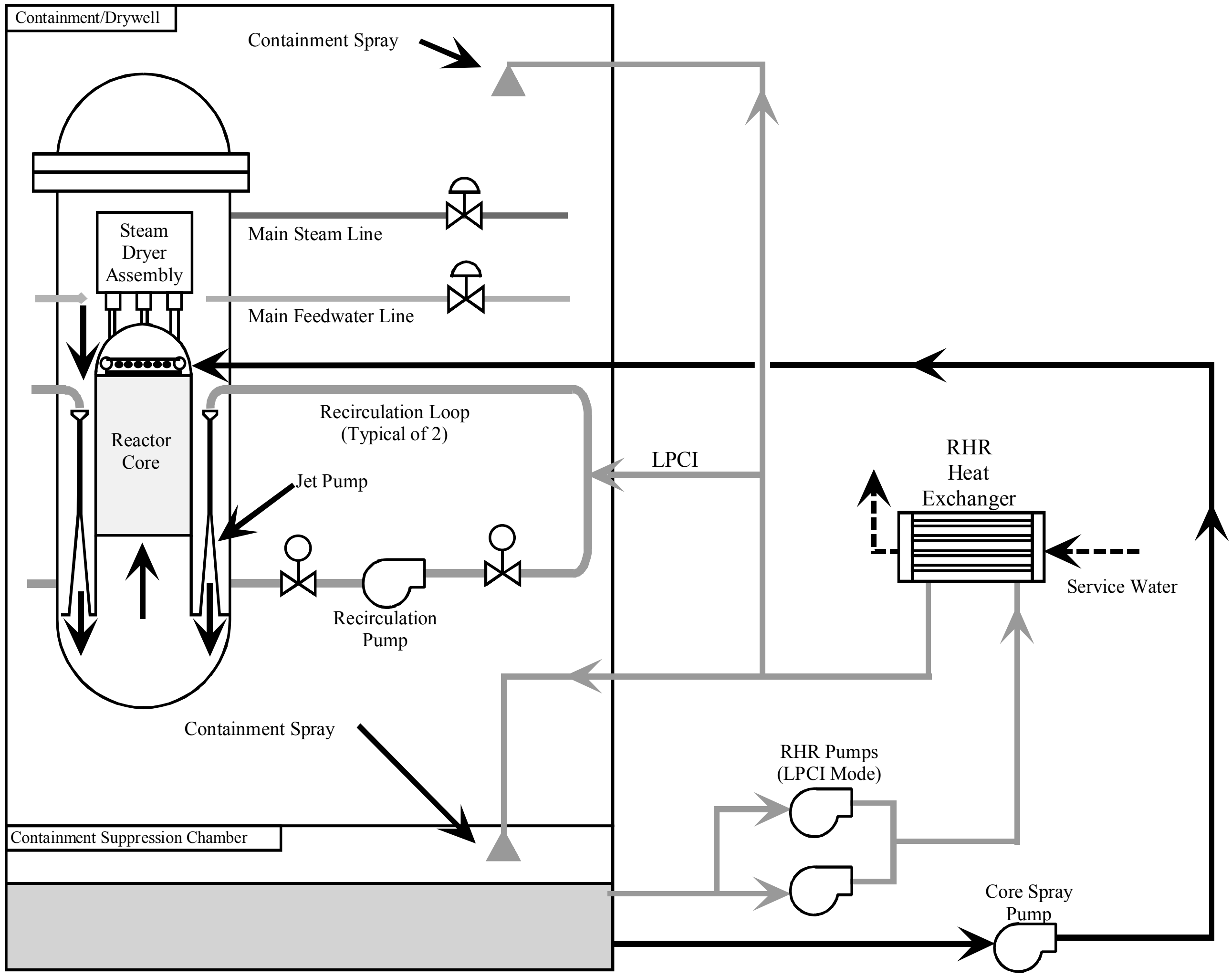
Emergency Core Cooling System Network



High Pressure Emergency Core Cooling Systems

The high pressure coolant injection (HPCI) system is an independent emergency core cooling system requiring no auxiliary ac power, plant air systems, or external cooling water systems to perform its purpose of providing make up water to the reactor vessel for core cooling under small and intermediate size loss of coolant accidents. The high pressure coolant injection system can supply make up water to the reactor vessel from above rated reactor pressure to a reactor pressure below that at which the low pressure emergency core cooling systems can inject.

The automatic depressurization system (ADS) consists of redundant logics capable of opening selected safety relief valves, when required, to provide reactor depressurization for events involving small or intermediate size loss of coolant accidents if the high pressure coolant injection system is not available or cannot recover reactor vessel water level.



Low Pressure Emergency Core Cooling Systems

The low pressure emergency core cooling systems consist of two separate and independent systems, the core spray system and the low pressure coolant injection (LPCI) mode of the residual heat removal system. The core spray system consists of two separate and independent pumping loops, each capable of pumping water from the suppression pool into the reactor vessel. Core cooling is accomplished by spraying water on top of the fuel assemblies.

The low pressure coolant injection mode of the residual heat removal system provides makeup water to the reactor vessel for core cooling under loss of coolant accident conditions. The residual heat removal system is a multipurpose system with several operational modes, each utilizing the same major pieces of equipment. The low pressure coolant injection mode is the dominant mode and normal valve lineup configuration of the residual heat removal system. The low pressure coolant injection mode operates automatically to restore and, if necessary, maintain the reactor vessel coolant inventory to preclude fuel cladding temperatures in excess of 2200EF. During low pressure coolant injection operation, the residual heat removal pumps take water from the suppression pool and discharge to the reactor vessel.

Boiling Water Reactor Containments

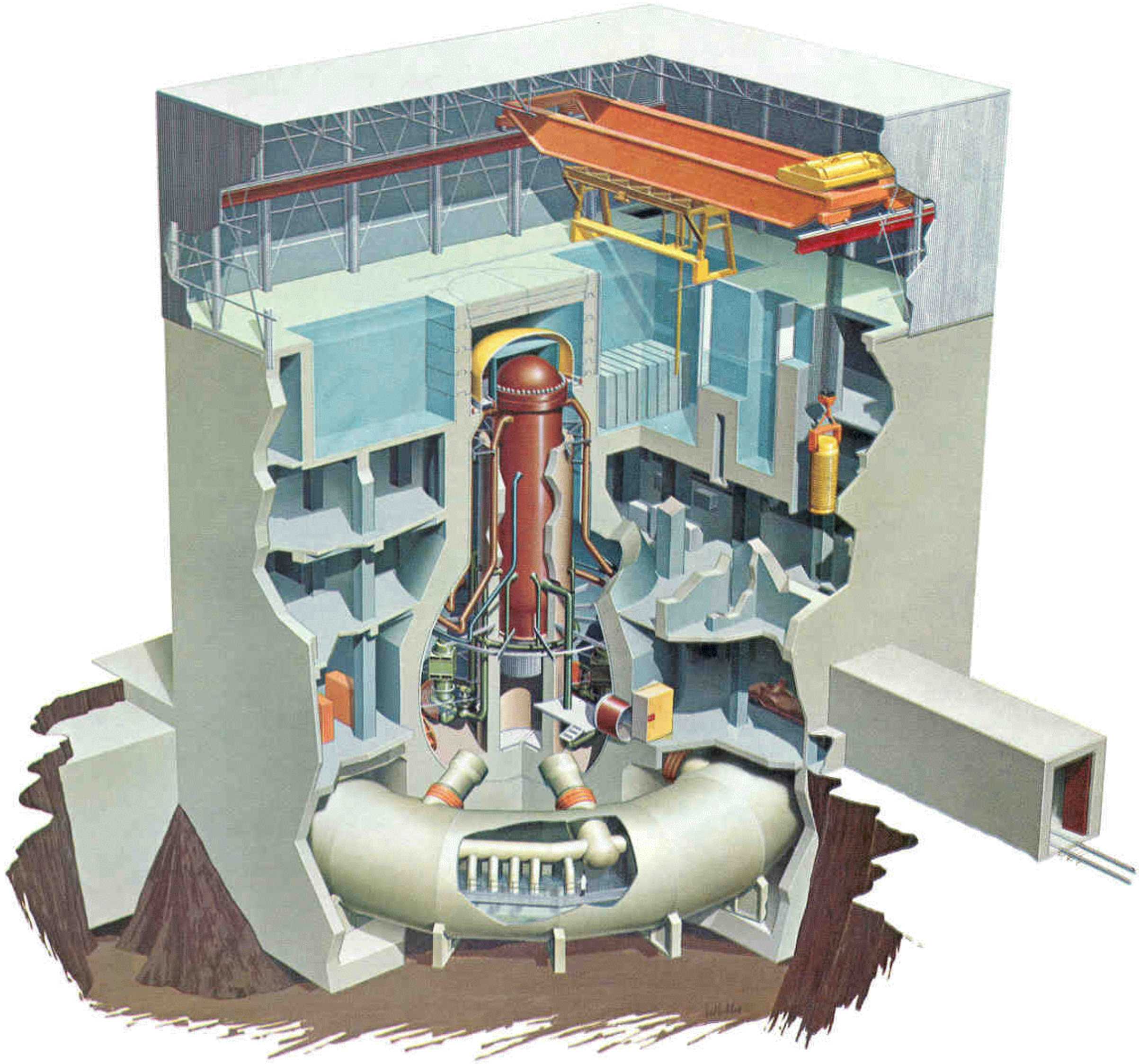
The primary containment package provided for a particular product line is dependent upon the vintage of the plant and the cost-benefit analysis performed prior to the plant being built. During the evolution of the boiling water reactors, three major types of containments were built. The major containment designs are the Mark I (page 3-16), Mark II (page 3-17), and the Mark III (page 3-18). Unlike the Mark III, that consists of a primary containment and a drywell, the Mark I and Mark II designs consist of a drywell and a wetwell (suppression pool). All three containment designs use the principle of pressure suppression for loss of coolant accidents. The primary containment is designed to condense steam and to contain fission products released from a loss of coolant accident so that offsite radiation doses specified in 10 CFR 100 are not exceeded and to provide a heat sink and water source for certain safety-related equipment.

The Mark I containment design consists of several major components, many of which can be seen on page 3-16. These major components include:

- The drywell, which surrounds the reactor vessel and recirculation loops,
- A suppression chamber, which stores a large body of water (suppression pool),
- An interconnecting vent network between the drywell and the suppression chamber, and
- The secondary containment, which surrounds the primary containment (drywell and suppression pool) and houses the spent fuel pool and emergency core cooling systems.

The Mark II primary containment consists of a steel dome head and either a post-tensioned concrete wall or reinforced concrete wall standing on a base mat of reinforced concrete. The inner surface of the containment is lined with a steel plate that acts as a leak-tight membrane. The containment wall also serves as a support for the floor slabs of the reactor building (secondary containment) and the refueling pools. The Mark II design is an over-under configuration. The drywell, in the form of a frustum of a cone or a truncated cone, is located directly above the suppression pool. The suppression chamber is cylindrical and separated from the drywell by a reinforced concrete slab. The drywell is topped by an elliptical steel dome called a drywell head. The drywell inerted atmosphere is vented into the suppression chamber through as series of downcomer pipes penetrating and supported by the drywell floor.

The Mark III primary containment consists of several major components, many of which can be seen on page 3-18. The drywell (13) is a cylindrical, reinforced concrete structure with a removable head. The drywell is designed to withstand and confine steam generated during a pipe rupture inside the containment and to channel the released steam into the suppression pool (10) via the weir wall (11) and the horizontal vents (12). The suppression pool contains a large volume of water for rapidly condensing steam directed to it. A leak tight, cylindrical, steel containment vessel (2) surround the drywell and the suppression pool to prevent gaseous and particulate fission products from escaping to the environment following a pipe break inside containment.

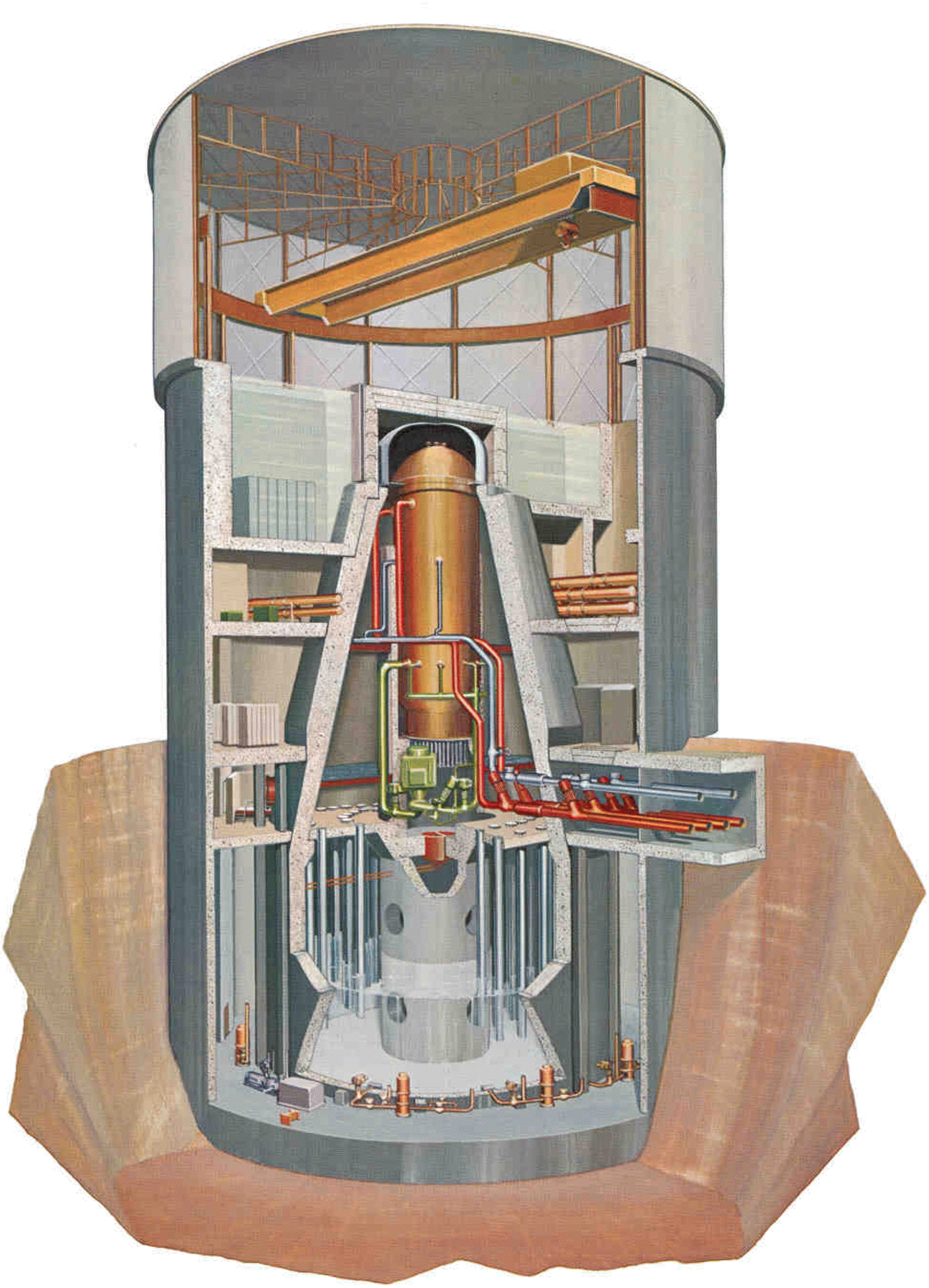


DRYWELL TORUS

GENERAL ELECTRIC

GEZ-4396

Mark I Containment

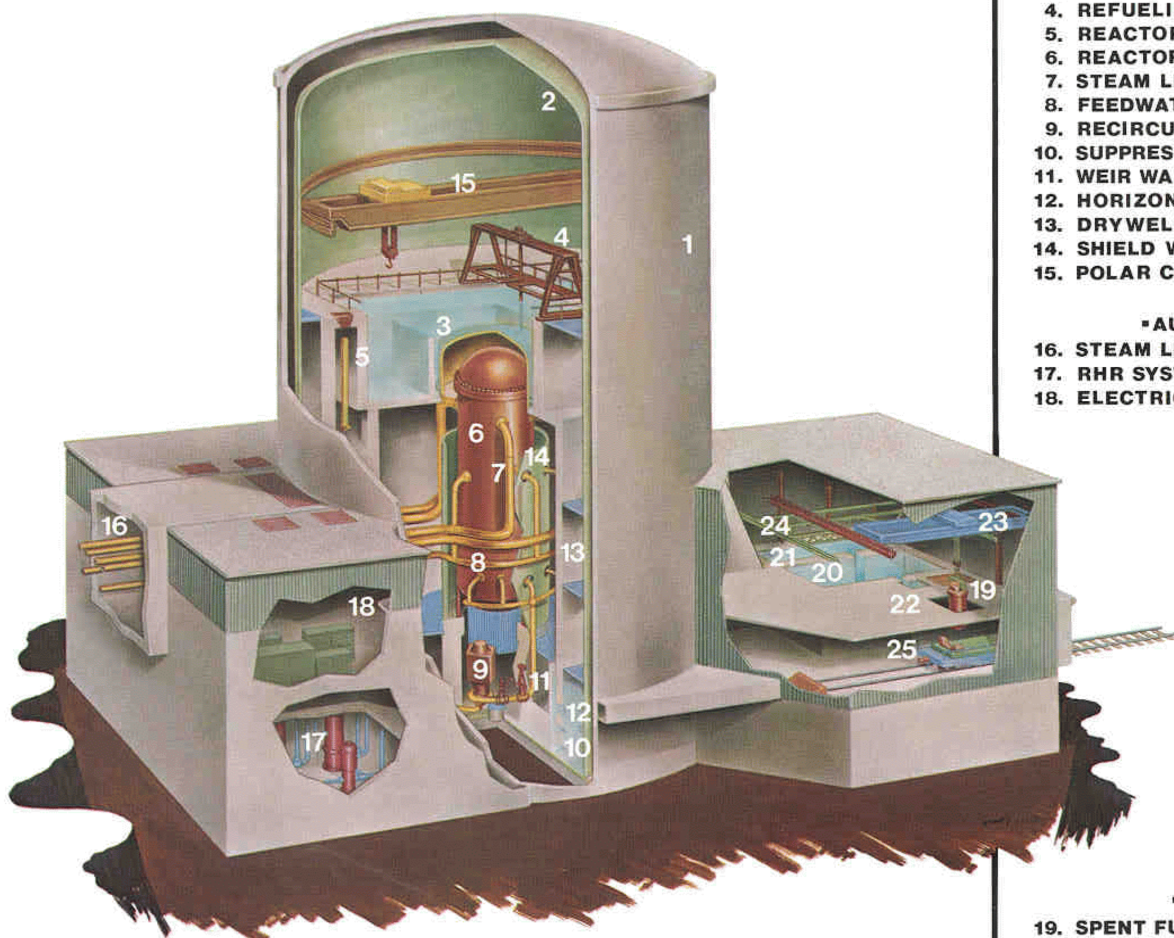


GENERAL ELECTRIC

GEZ-4370

Mark II Containment

MARK III CONTAINMENT



▪REACTOR BUILDING▪

1. SHIELD BUILDING
2. FREESTANDING STEEL CONTAINMENT
3. UPPER POOL
4. REFUELING PLATFORM
5. REACTOR WATER CLEANUP
6. REACTOR VESSEL
7. STEAM LINE
8. FEEDWATER LINE
9. RECIRCULATION LOOP
10. SUPPRESSION POOL
11. WEIR WALL
12. HORIZONTAL VENT
13. DRYWELL
14. SHIELD WALL
15. POLAR CRANE

▪AUXILIARY BUILDING▪

16. STEAM LINE TUNNEL
17. RHR SYSTEM
18. ELECTRICAL EQUIPMENT ROOM

▪FUEL BUILDING▪

19. SPENT FUEL SHIPPING CASK
20. FUEL STORAGE POOL
21. FUEL TRANSFER POOL
22. CASK LOADING POOL
23. CASK HANDLING CRANE
24. FUEL TRANSFER BRIDGE
25. FUEL CASK SKID ON RAILROAD CAR

GENERAL ELECTRIC

GEZ-4385.1

Mark III Containment